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Wettability conundrum: Discrepancies of soft contact lens performance *in vitro* and *in vivo*

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Abstract. The recognition and appreciation of soft contact lenses as simple, efficient and aesthetically gratifying vision-correction devices is ever growing, especially among younger population. Stable thin tear film uniformly spread over corrective lens surface is essential for acute vision, and also for comfortable and safe contact lens wear. The significant efforts have been invested by the contact lens industry to develop soft lens surface that is completely wet by tear aqueous in the ocular environment. Number of the publications dedicated to the wettability properties of the soft hydrogel lenses is on the steady rise. However, the clinical results show that no unambiguous correlation emerges when lens surface wettability *in vitro* is judged against tear film stability evaluated *in vivo*. This paper assesses and compares the modern techniques used for evaluation of soft contact lens surface wettability and reports some findings regarding relations between lens surface wettability *in vitro* and *in vivo*.

1 Introduction

The important features in maintaining good ocular health and acute vision are tear film stability and uniform coverage of the corneal surface by tears. Tear films laden with proteins and other biologically active components subsist under highly dynamic conditions. These thin aqueous films are periodically subjected to dilatational and shear stresses induced by eyelid movement during blinks that occur usually 5 to 10 seconds apart. Theoretical relationships among tear breakup time and liquid film physical properties such as viscosity, surface tension, meniscus radius, and initial and final film thicknesses have been described [1]. The model used in this paper implies that tear film is destined to rupture through evaporative film thinning and/or inherent hydrodynamic instabilities. The popularity of soft contact lenses for vision correction is steadily growing ever since safer and more comfortable lenses were developed and introduced into the market. However, when used, contact lenses inevitably alter tear-film properties and stability. Insertion of a contact lens onto an eye divides already thin tear film into two even thinner fractions – the pre-lens and post-lens tear films. A thinner fluid film is more susceptible to spontaneous rupture [1–4]. An important

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practical and clinical implication emerges because discomfort reported by patients during contact lens wear has been linked to fast tear-film breakup [5].

Effective and full tear-film recovery after blink is believed to depend on the wettability of the ocular surface [6–8] or, in the case of contact lenses, on the lens-surface wetting properties [9–14]. As a result, the contact lens industry has invested significant research efforts into developing a soft lens surface that is highly wettable, hence biocompatible, in the ocular environment.

The most widely used approach to characterize the wettability of a solid surface is through the measurements of contact angle. In clinical practice among eye care practitioners, it is commonly believed that the wetting behavior of an aqueous drop on soft contact lens surface as assessed by contact angles can predict the performance of a contact lens *in vivo*: the lower the contact angle, the better the wettability of the lens surface, and consequently enhanced stability of the tear film on the lens surface should be expected. Soft contact lenses put forward substantial technical challenges when it comes to contact-angle measurements. First, these lenses are made of highly porous hydrogel polymeric materials and contain from 24% (Lotrafilcon A, Focus Night&Day, CIBA Vision Inc.) up to 74% (Precision UV, CIBA Vision Inc.) of aqueous phase. Second, they are distributed by the manufacturers and sold in stores in blister packs filled with a liquid, which is either buffered isotonic sodium chloride solution with some preserving and/or disinfecting agents; or, in some lens-brands, these solutions may contain surface-active additives (non-specified, proprietary information) introduced for wettability improvement [15,16]. In addition, the lens surface is curved unevenly to furnish a specific optical power and to provide proper vision correction. Moreover, the lens surface might be physically rough and chemically heterogeneous. The combination of these factors: surface curvature, high porosity, physical and chemical heterogeneity, and presence of surface-active ingredients make contact-angle measurements beyond a doubt challenging and hence the results reported in the literature are often contradictory and ambiguous [11–17]. Any surface chemist would find a serious deficiency in the publications describing soft contact lenses wettability *in vitro*, namely, the lack of surface tension values measured and reported in conjunction with contact-angle values.

The cosine of the contact angle of a liquid drop resting on a solid surface and in equilibrium with a surrounding vapor (gas phase) is determined by Young's Equation [18]:

$$\cos\theta_e = (\gamma_{SV} - \gamma_{SL})/\gamma_{LV}, \tag{1}$$

where θ_e is the equilibrium contact angle, and γ_{SV}, γ_{SL}, are the interfacial tensions between the solid and the vapor, and the solid and the liquid, respectively, and γ_{LV} is the surface tension of the liquid. The expression in parenthesis, $(\gamma_{SV} - \gamma_{SL})$, is a specific property of a solid-liquid interface and is usually referred to as adhesion tension; it characterizes the propensity of a liquid attraction toward a solid. When the liquid wets the solid surface completely (i.e., spreads spontaneously over the solid surface and forms a thermodynamically stable film with zero contact angle), the adhesion tension is numerically equal to the surface tension of the spreading liquid, which is 72.4 mN/m for pure water at room temperature. Contact angles alone, as one can see from Young's Eq. (1), do not provide a true estimate of surface wettability unless the surface tension of the test liquid is taken into account. Reported in the literature contact angles values measured on soft contact lenses are often controversial and inconsistent besides being unaccompanied by surface tension measurements. The resolution of these controversies in contact-angle measurements is further complicated by different measurement techniques and/or different media in which measurements were conducted [11–17].

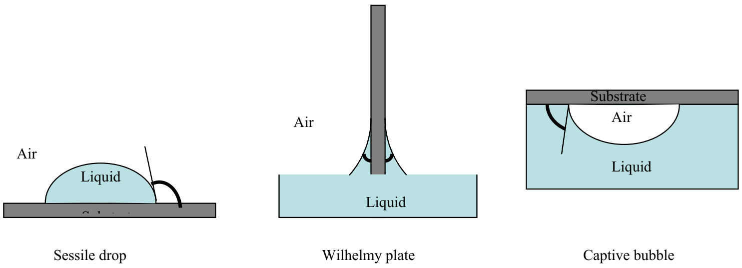

Fig. 1. Schematics of three different configurations used for contact-angle measurements.

2 Materials and methods

The commercially available soft contact lenses were used in our study. They are listed in Table 1. The major techniques reported for contact-angle assessment on soft contact lenses are sessile drop, Wilhelmy plate, and captive bubble [11–17]. Figure 1 illustrates the schematics of these techniques. Neither of them is ideal, each has its own set of advantages and shortcomings. Sessile drop method is the most popular because it is fast, can be used for the measurements on a whole intact soft contact lens, is relatively user-friendly, and several commercially available computer-controlled instruments (for instance, DSA from Kruss, Germany/USA, DropImage goniometer from Rame-Hart, USA) are supplied with software for contact-angle measurements on flat surfaces. One of the main problems with this technique is its short available experimental time, typically up to 10 seconds, since drop evaporation/permeation into lens matrix leads to fast-changing contact angles. Therefore, the contact angles measured using sessile drop represent some transient values observed at an arbitrarily chosen time and are far from static or equilibrium values. There are other issues making sessile drop results ambiguous namely dehydration of a lens surface happening in a course of measurements possibly affects surface wettability. Additionally, the combination of low (below 20°) contact angles and lens-surface curvature renders the contact-point position practically indistinguishable and undeterminable, thus making accurate contact-angle measurements impossible. Wilhelmy plate method is free of lens-surface curvature problems. However, it is more cumbersome and requires certain manipulations with the lens – cutting the lens into strips and hanging these strips stretched and suspended partly in aqueous phase and in air – that might lead to some changes in lens-surface properties.

Captive bubble technique eliminates the dehydration issue since the lens is completely immersed into the aqueous phase during experiments; however, the captive bubble method used by Maldonado-Codina et al. [15]. allowed the measurements of only static water-receding angles. This technique was implemented with bubble-volume control and allowed measurements of both advancing and receding contact angles on flattened lens surface [19]. We modified this instrument to make it more suitable for contact angle measurements on a curved lens surface under dynamic conditions with an option of concurrent surface tension evaluation [20]. The schematics of our modified captive bubble instrument are shown in Fig. 2. The detailed description of this instrument can be found elsewhere [20]. In our instrument, a lens is placed in a holder resting at the bottom of the optical cell and is equipped with a magnetic stirring bar to rotate the lens holder inside the cell. This setup makes it significantly different and easier to use than setup for the captive bubble introduced by Cheng et al. [19] where the lens was mounted upside down inside the cell. Additionally, a big air bubble is suspended and brought into contact with a lens from above. The topmost part of a bubble remains pinned inside a cavity of a bubble holder so that only the bubble/lens contact line is moving along a lens surface during contact-angle

Table 1. Soft contact lens materials and specifications.

Lens Brand Name (Abbreviation) Material (Manufacturer)	Surface Treatment	% H_2O	Contact angles and Adhesion Tension, Mean ±SD (mN/m)		Contact Angle, literature, °	Surface Tension of packaging solutions Mean ±SD (mN/m)
			From Blister	Pre-soaked		
Accuvue 2 (AV2) Etafilcon A (Vistakon)	None	58	11° ± 3.1° 43.5 ± 6.4	83.7° ± 4.5° 8.7 ± 2.3	80 (presoaked)[^17] 37[#17] 81[*19]	53.5 ± 1.8
Biomedics 55 Premier (BM55) Ocufilcon D (Cooper Vision)	None	55	35.8° ± 11.3° 43.8 ± 8.3	71.2° ± 6.9° 17.8 ± 7.7		41.6 ± 1.5
Extreme H_2O (ExtH_2O) Hioxifilcon D (Hydrogel Vision)	None	54	55.6° ± 13.4° 31.7 ± 12.7	79.7° ± 8.1° 11.7 ± 9.6		37.9 ± 0.7
Proclear Omafilcon A (Cooper Vision)	None	62	48.5° ± 7.4° 40.4 ± 8.4	57.6° ± 9.1° 34.9 ± 8.8	95[#17]	59.8 ± 2.5
Silicone Hydrogels						
AirOptix Night&Day (AOND) Lotrafilcon A (Ciba Vision)	None, (Aqua Moisture)	24	17.0° ± 7.4° 54.2 ± 3.9	30.1° ± 3.8° 54.8 ± 1.1		68.1 ± 1.0
Accuvue Advance (AVA) Galyfilcon A (Vistacon)	None, (Internal PVP)	47	34.9° ± 3.53° 39.3 ± 4.3	39.3° ± 4.3° 54.0 ± 8.5	96.3[#15] 30.5[*15] 115[#17]	58.5 ± 2.3
Accuvue Oasys (AVO) Senofilcon A (Vistacon)	None, (Internal PVP)	38	16.5° ± 7.5° 47.7 ± 3.9	27.7° ± 5.3° 54.3 ± 4.4	85.0[#15] 32.4[*15] 90[#17]	46.5 ± 1.5
Biofinity Comfilcon A (Cooper Vision)	None	48	12.8° ± 4.5° 50.4 ± 4.9	20.9° ± 9.3° 58.3 ± 5.9		44.5 ± 0.4
Focus Night&Day (FND) Lotrafilcon A (Ciba Vision)	Plasma coating	24	4.28° ± 4.4° 47.2 ± 2.6	42.5° ± 5.2° 49.8 ± 3.8	43.9[#15] 41.0[*15] 43[#17] 61[*19]	66.5 ± 0.6
O_2Optix (O_2O) Lotrafilcon B (Ciba Vision)	Plasma coating	33	35.9° ± 2.4° 48.5 ± 4.5	48.7° ± 3.8° 44.2 ± 4.5	37.2[#15] 44.3[*15] 36[#17]	70.3 ± 0.6
Pure Vision (PV) Balafilcon A (Bausch&Lomb)	Plasma oxidation	36	82.9° ± 15.1° 14.5 ± 28.5	74.4° ± 9.3° 17.8 ± 10.2	101.6[#15] 30.1[*15] 120[#17] 81[*19]	70.0 ± 0.2

– sessile drop
∗ – captive bubble.
∧ – Wilhelmy plate

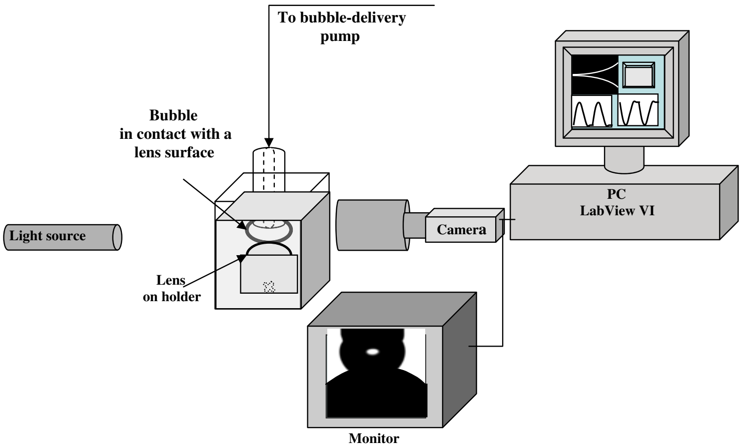

Fig. 2. Schematics of modified captive bubble instrument.

measurements. In previously reported works [11–19] both advancing and receding contact angles were measured on a small portion of a soft-contact-lens surface, typically close to lens-center. In contrast, our technique permitted to study wettability dynamics over a relatively large part (up to 75% of total) of a lens surface, with several reiterations of three-phase contact line advancing and receding along the lens surface [20]. We also employed this technique to concurrently measure the surface tension at the aqueous-air interface. With this new experimental approach we characterized the surface wettability of several HEMA-copolymers-based and silicone-hydrogel soft contact lenses using adhesion tension as a universal, physically meaningful gauge of surface wettability.

3 Results and discussion

The silicone polymers are rather hydrophobic materials, for instance, contact angle of pure water on the surface of untreated silicone rubber may be as high as 120°. To enhance silicone hydrogel lens wettability, the plasma oxidation of lens surface is applied for some lens brands (e.g., PureVision and Focus Night&Day); for other materials, hydrophilic co-polymers are introduced into the lens material (e.g., Acuvue Advance, Acuvue Oasys). These treatments are proven to be efficient and render the surface of silicone hydrogel lenses more hydrophilic than that of conventional HEMA-based hydrogel lenses, as one can see from Table 1, where our results are summarized along with literature data when available.

The examples of contact lens-surface morphology of silicone hydrogel lenses are presented in Figs. 3(a–c), where we show the atomic force microscopy (AFM) images of the three silicone hydrogel lens surfaces: Balafilcon A (Pure Vision, Bausch & Lomb, USA), Galyfilcon A (Acuvue Advance, Vistakon, USA) and Senofilcon A (Acuvue Oasys, Vistakon, USA).

These images represent the height data, obtained using tapping mode in air for dry-lens surfaces. One can clearly see that the surface topography is drastically different among these lenses. Note that PureVision and Acuvue Oasys lenses have comparable water contents, 36% and 38%, compared with 47% for Acuvue Advance. The topographical differences affect the contact-angle dynamics examined using a modified captive bubble setup. The contact-angle hysteresis loops, i.e., the dynamic contact-angle values measured when the bubble was expanding (water-receding angles) and

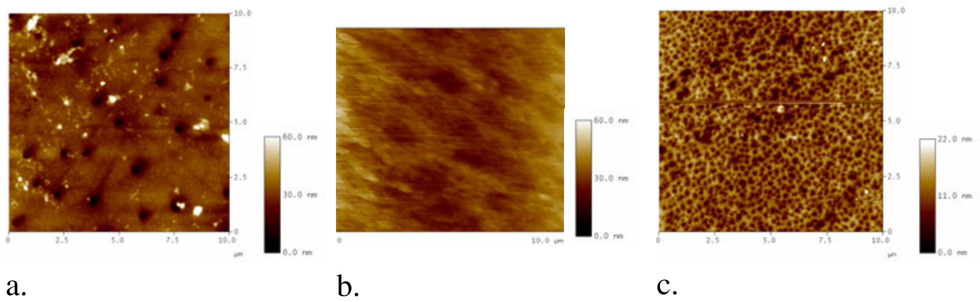

Fig. 3. AFM images (height data, taping mode in air) of silicone hydrogel lenses surfaces: **a.** PV; **b.** Acuvue Advance; **c.** Acuvue Oasys.

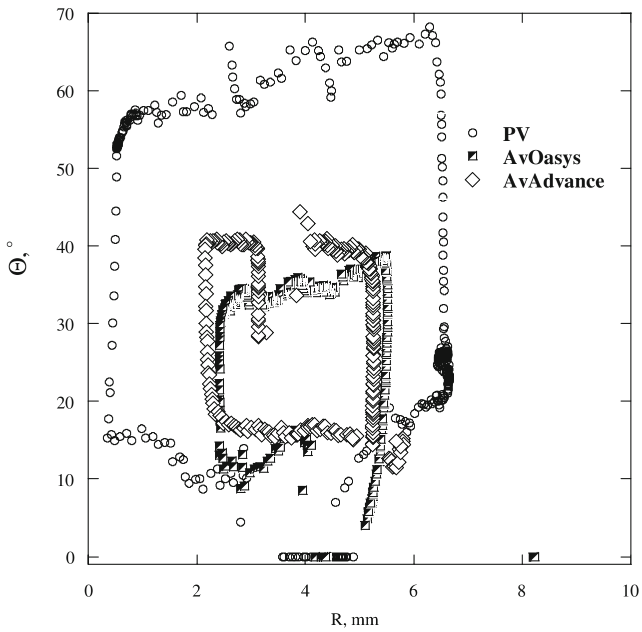

Fig. 4. Contact angle hysteresis on PV, Acuvue Oasys and Acuvue Advance lenses.

contracting (water-advancing angles) plotted as a function of contact-point distance from lens center, are presented in the Fig. 4. These measurements were performed in surfactant-free aqueous buffered electrolyte solution (OptiFree, Alcon, USA) on the same lenses for which AFM images (Figs. 3(a–c)) were obtained afterward. One can see that advancing contact angles are high for PureVision lenses and contact line movement tends to be stick-slip on this lens.

For Acuvue Advance, water-advancing angle is lower and some stick-slip movement observed at certain points on the surface. The lowest advancing angles and smoothest motion of contact line over the lens surface was observed on Acuvue Oasys lens, which has the smallest and most evenly distributed surface irregularities (small dimples pictured as darker spots on AFM images).

As mentioned above, in the lens manufacturing industry several approaches are used to enhance surface wettability of soft contact lenses. The traditional method developed for HEMA co-polymer lenses is to add surface-active wetting agents into lens packaging or lens care solutions. Wetting agents adsorbed on the lens surface

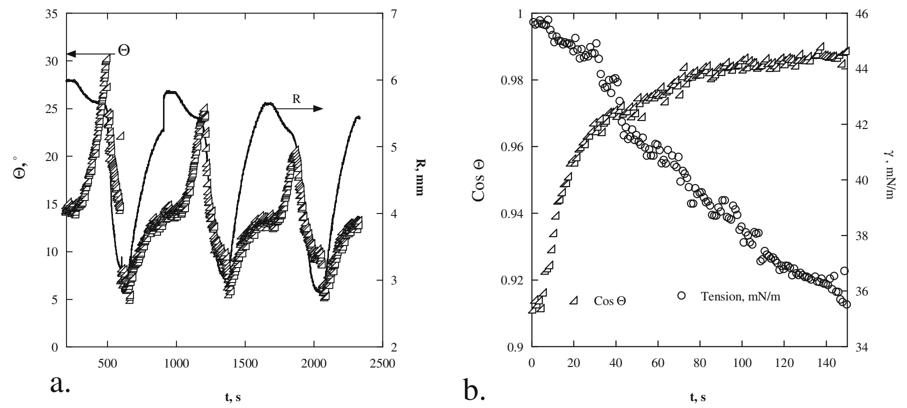

Fig. 5. a. Three cycles of contact line advancing and receding on Acuvue 2 lens. Line represents the contact point position and open triangles - contact angles. **b.** Surface tension and contact angle cosine dynamics for aqueous phase advancing on Acuvue 2 lens.

are expected to improve the wettability of the lens surface. When present in blister solutions, the surface-active agents penetrate and accumulate inside the porous lens matrix. Once the lens is immersed into surfactant-free media, these surfactants will gradually "leach" into aqueous media and adsorb at air-aqueous interface causing surface tension reduction. This, according to Eq. (1), will affect the contact angle of aqueous phase on the lens surface.

Figure 5(a) exemplifies the influence of surface-active additives released into an aqueous media and adsorbed at the air-aqueous interface on dynamic contact angles. Here the contact-angle values measured on Acuvue 2 lens immersed in OptiFree solution are plotted as a function of the bubble-lens contact time, with the measurements taken soon after lens removal from a blister-pack solution. It is clearly discernible how much the advancing contact angles change within each cycle and from the first to the following cycles of three-phase contact line movements.

Figure 5(b) exhibits the changes in surface tension and contact-angle cosine occurring during contraction of a bubble (previously fully blown and equilibrated while in contact with Acuvue 2 lens). It is apparent that depicted in Fig. 5(a) advancing angle decrease is dictated by the concurrent surface tension reduction happening when bubble is shrinking. The surface tension continues to slowly decrease while the air-aqueous interface becomes more populated with surfactant molecules as additional surface-active molecules are released from lens matrix. As a result, transient contact-angle values reported when the interfaces were not properly equilibrated are inexorably accompanied by contradictions and inconsistencies [11–18]. The interface equilibration is not quite possible when sessile drop technique is used; however, the modified captive bubble method provides the possibility to conduct long-time experiments thus ensuring the interface equilibration.

As our previous study [20] revealed, it took seven days of soaking in surfactant-free solution with daily solution replacement to remove most of surface-active additives from Acuvue 2 and some other HEMA-based conventional contact lenses. By the end of this process, the wettability of HEMA-based contact lenses was dramatically reduced, as reported in Table 1. For silicone hydrogel lenses the surface wettability is found to remain practically unchanged after prolonged soaking in surfactant-free media. In contrast with HEMA-based lenses, the surface properties of the silicone hydrogel lenses are not dependent on surface-active additives in packaging solutions.

It is interesting to note that, as one can see from Table 1, Focus Night and Day lenses were the only lenses packed in surfactant-free solution. For these

Table 2. Summary of *in vitro* and *ex vivo* wettability measurements for Acuvue 2 lenses.

	In vitro	unworm	lenses	*Ex vivo*	worn	lenses
Accuvue 2	Θ_A, °	Surface Tension (mN/m)	Adhesion Tension (mN/m)	Θ_A, °	Surface Tension (mN/m)	Adhesion Tension (mN/m)
Pre-soak for 7 days	83.7 ± 4.5	57.1 ± 3.1	6.6 ± 2.5	22.3 ± 9.8	41.4 ± 4.3	37.6 ± 4.0
Pristine from blister	10.9 ± 3.1	42.3 ± 1.1	44.6 ± 2.1	9.4 ± 4.6	40.8 ± 6.3	40.1 ± 6.1

surfactant-free lenses there was good agreement between advancing angle values determined by using our modified captive bubble instrument and other techniques [15–17]. However, since the completion of a series of our studies, the manufacturer of these lenses, CIBA Vision, USA, has changed the composition of blister-pack solution by adding some surfactants in it. Thus, Focus Night and Day lenses we studied are no longer available, having been replaced with AirOptix Night and Day lenses.

To elucidate the role of lens-surface wettability on tear-film stability and lens-wear comfort, a series of clinical studies were conducted using soft contact lenses indistinguishable in all properties but with distinctly different surface wettability [21]. In this study, we examined the relationships among lens-wear comfort, tear-film stability, and wettability of two identical Acuvue 2 lenses worn by the subjects contra-laterally. The one lens was taken directly from blister solution and the other was pre-soaked in a surfactant-free lens care solution (OptiFree) for 7 days prior to lens insertion onto an eye. Initially, as one can conclude from Table 2, each person had in one eye a lens with significantly lower adhesion tension, thus poorer wettability, than the lens in the other eye. The non-invasive tear-film breakup time was measured prior to and 30 minutes after lens insertion by projecting placido rings (Humphrey photokeratoscope, USA) onto the tear film to measure the time it takes for the reflected rings to be distorted or broken during inter-blink period.

It was found [21] that the subjects could not make conclusive distinctions regarding comfort and dryness sensations between these two lenses. The clinicians also could not clearly differentiate these lenses in regard to their clinically-assessed wettability. Pre-lens tear breakup time was 2-3 times shorter than pre-corneal, and on average the breakup time reduction was the same for both pristine lenses from blister (with surfactants) and pre-soaked ones (without surfactants). Moreover, when the worn lenses were collected and the contact angles were measured *ex vivo*, the difference in adhesion tension, which existed before these lenses were worn, completely disappeared. These results are summarized in Table 2 [21].

Acuvue 2 lenses are prone to absorption of present-in-tear-fluid proteins and are able to accumulate up to 1 mg of proteins per lens at the end of day wear [22,23]. Tear proteins have some surface activity, and they can reduce surface tension at the water-air interface. This Acuvue 2 lens propensity to absorb tear proteins explains our findings in regard to surface tension reduction, especially for pre-soaked lens, observed after worn lenses were equilibrated with an air bubble during *ex vivo* contact-angle measurements. Analysis of the protein uptake by worn lenses performed using BCA colorimetric assay revealed that both pre-soaked and pristine lens absorb an equal amount, 31 ± 7.0 μg/lens, of tear proteins after 30 minutes of lens wear. During contact-angle measurements, these proteins were released from the lens and adsorbed at the aqueous-air interface, reducing the surface tension to 40 mN/m. Consequently, the initial difference of 38 mN/m in adhesion tension basically faded away and *ex vivo* adhesion tension of pristine and pre-soaked lenses became equal. These measurements of *ex vivo* contact angles in conjunction with surface and adhesion tension provided the explanation why the lenses with considerably different initial surface wettability have shown indistinguishable clinical performance when inserted onto an eye. The aqueous tear film is covered with outmost lipid layer which exhibits the surface tension of 22 ± 1 mN/m [25], that is low enough to guarantee complete wetting and spreading with zero contact angle even on relatively hydrophobic (with water-advancing contact angle up to 90°) surfaces of the contact lenses. As the result, the stability of the thin tear film spread over a soft contact lens surface becomes independent on lens-surface properties, while tear-film stability remains dependent on pre-lens film thickness, composition and quality of the tear film, ambient humidity, and other external factors.

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